Ionizing Radiation

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This is the reason why nuclear science education is so important.

MARIE CURIE
Nothing in life is to be feared, it is only to be understood.
Now is the time to understand more, so that we may fear less.

It’s the antidote for radiophobia – and the nemesis of those who want us to remain fearful of all things nuclear.

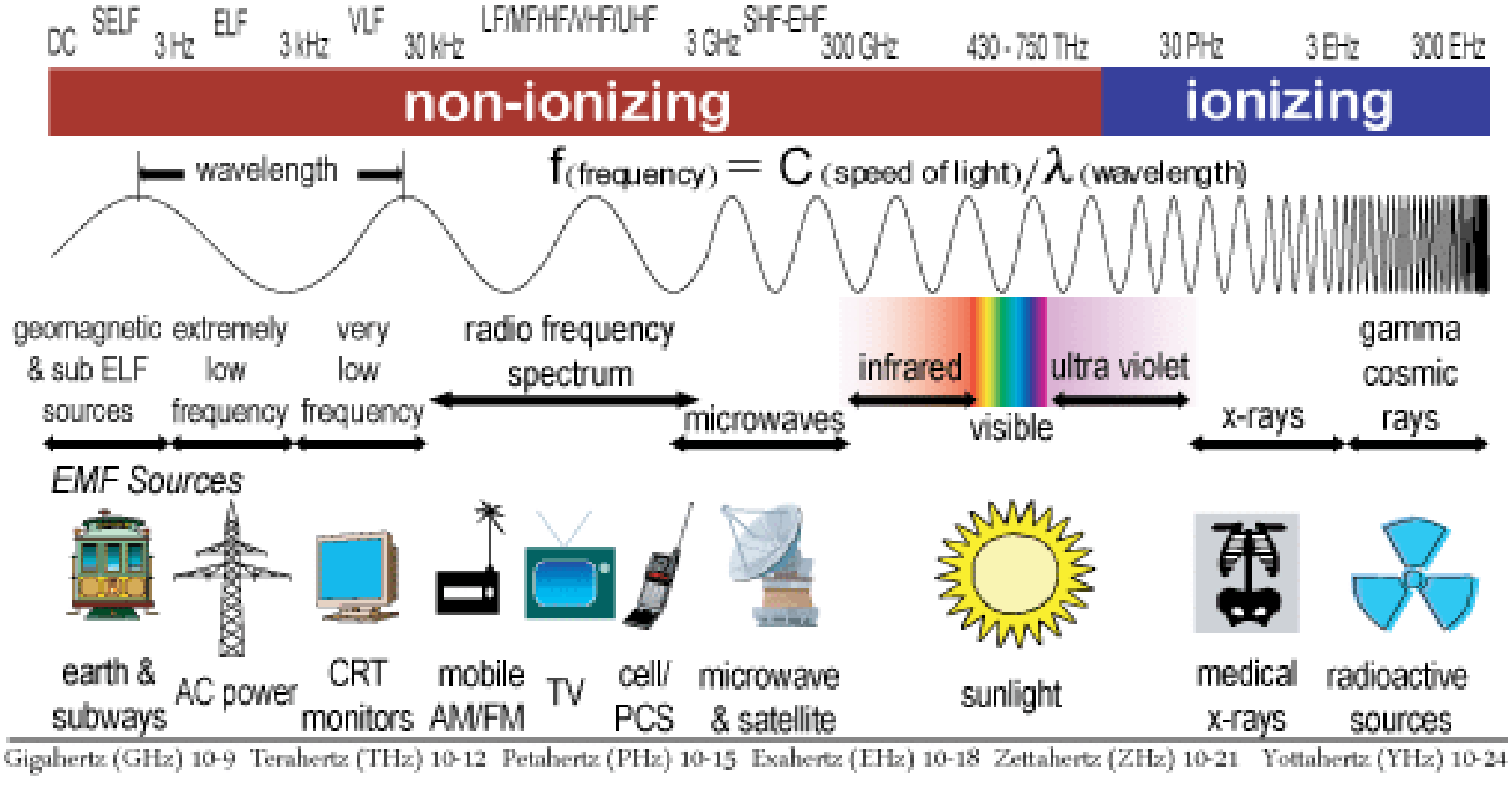
Terminology

- Radioactive decay – process by which an unstable atomic nucleus achieves a more stable state by emitting energy (radiation) in the form of subatomic particles or electromagnetic waves
- Radioactivity – emission of radiation from unstable atomic nucleus as it decays to more stable state
- Activity – measurement of rate of radioactive decay, defined as number of disintegrations per second
  - One Becquerel equals one decay per second

Ionizing & Non-Ionizing Radiation

- Ionizing Radiation: energy transmitted by subatomic particles or electromagnetic waves sufficient to dislodge orbital electrons in atoms, thereby producing ions and free electrons
- Non-Ionizing Radiation: electromagnetic waves with insufficient energy to dislodge orbital electrons in atoms
  - All electrical devices emit non-ionizing radiation (see electromagnetic spectrum)

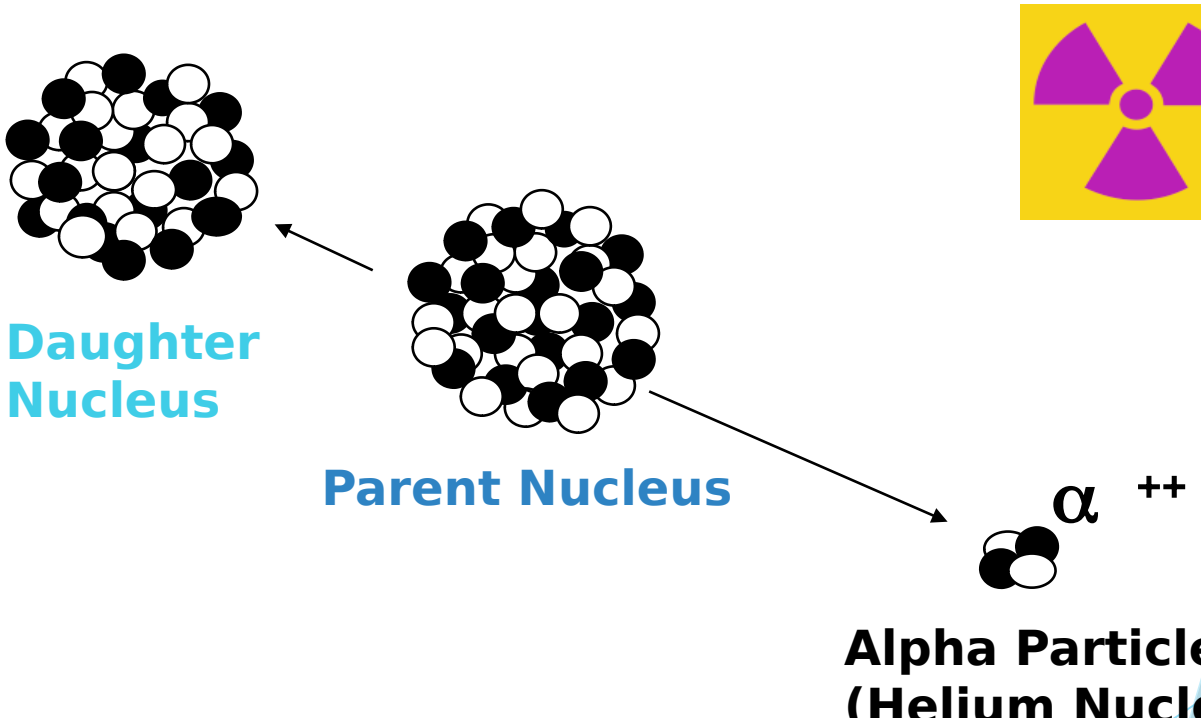
Electromagnetic Spectrum



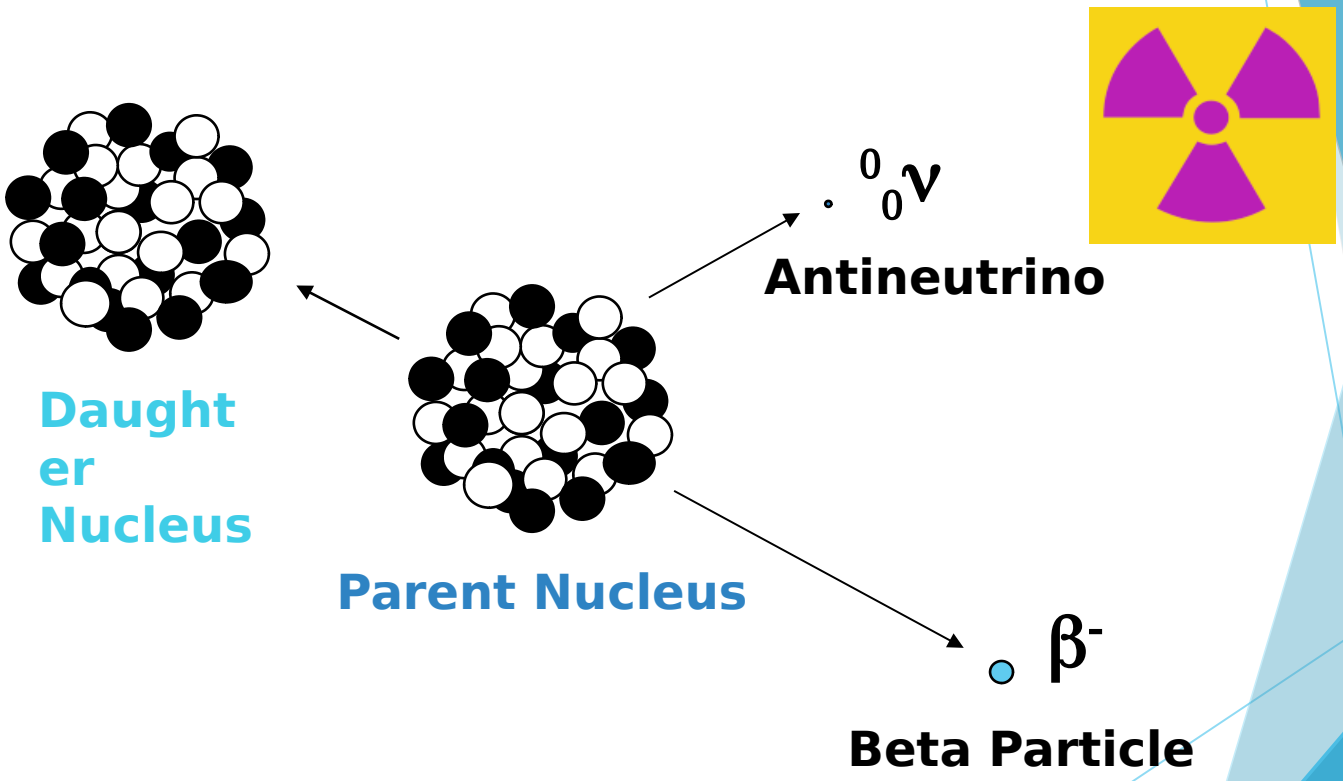
Types of Ionizing Radiation

- Alpha Particle – α
  - Helium nucleus (2 protons & 2 neutrons)
- Beta Particle – β
  - Energetic electron emitted from atomic nucleus when a neutron converts to a proton and an electron
- Gamma Ray – γ
  - High energy electromagnetic wave emitted when nucleus of atom transitions from higher to lower energy state
- X-rays also form of ionizing radiation, but do not originate from radioactive decay

Alpha Particle Radiation



Beta Particle Radiation

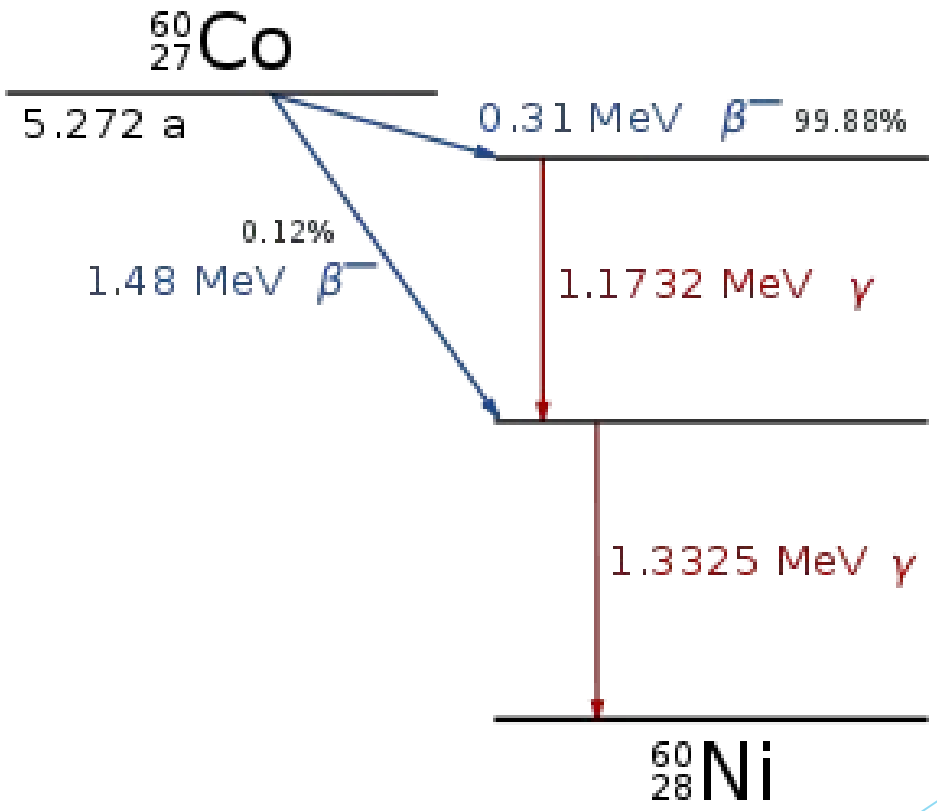


Gamma-ray Radiation

Gamma-ray radiation oftentimes accompanies alpha and beta radioactive decay processes in atoms

- Has no effect on number of protons or neutrons in daughter nucleus produced from particle decay
- Gamma-ray emission changes energy state of daughter nucleus from higher to lower energy or to ground energy state

Example Gamma-ray Emission Following Radioactive Decay



Quantifying Radioactivity

- Source strength of radioactive material, or activity (decay rate), is λN
  - λ is decay constant for particular radioisotope (usually expressed as disintegrations per second)
  - N is number of atoms of radioactive material
- Quantity λN known as activity of radioisotope
  - Activity expressed in units of Becquerel (Bq) or Curie (Ci)
  - 1 Bq = 1 atomic disintegration per second (dis/sec), 1 Ci = 3.7×10^{10} dis/sec

Decay Constant and Half-life

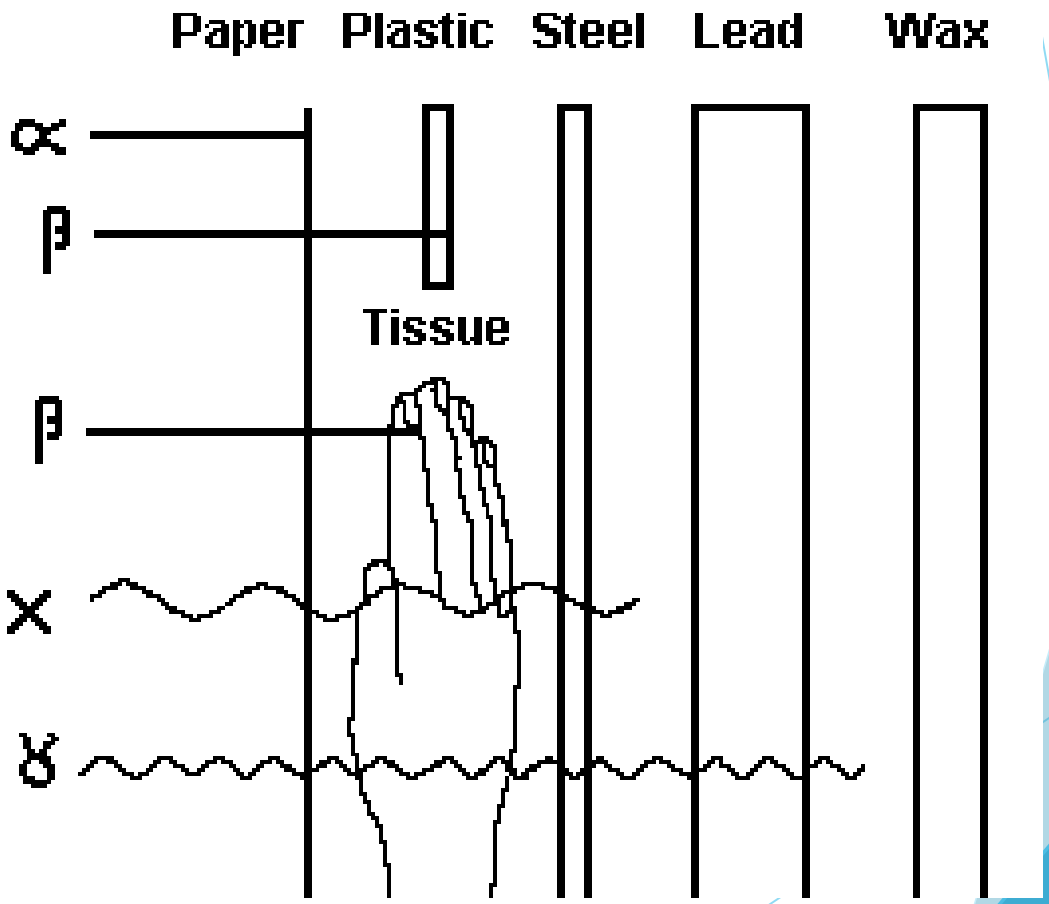
- Decay constant of radioactive isotope calculated from its half-life ($\lambda = 0.693/t_{1/2}$)
  - Radioisotope half-life is experimentally observed quantity of time it takes for one-half of radioactive atoms to decay
  - Radioisotope activity (i.e., decay rate) directly proportional to decay constant (i.e., large $\lambda \rightarrow$ large activity) and inversely proportional to half-life (i.e., short half-life $\rightarrow$ large activity)
- Very small quantities (N) of any radioactive material generally not health hazard (e.g., radioactive consumer products like granite counter tops and radioactive sources like Co-60, Cs-137, and Po-210 that can be purchased for educational and laboratory use)

Radiation as Potential Health Hazard

Health effects dependent on

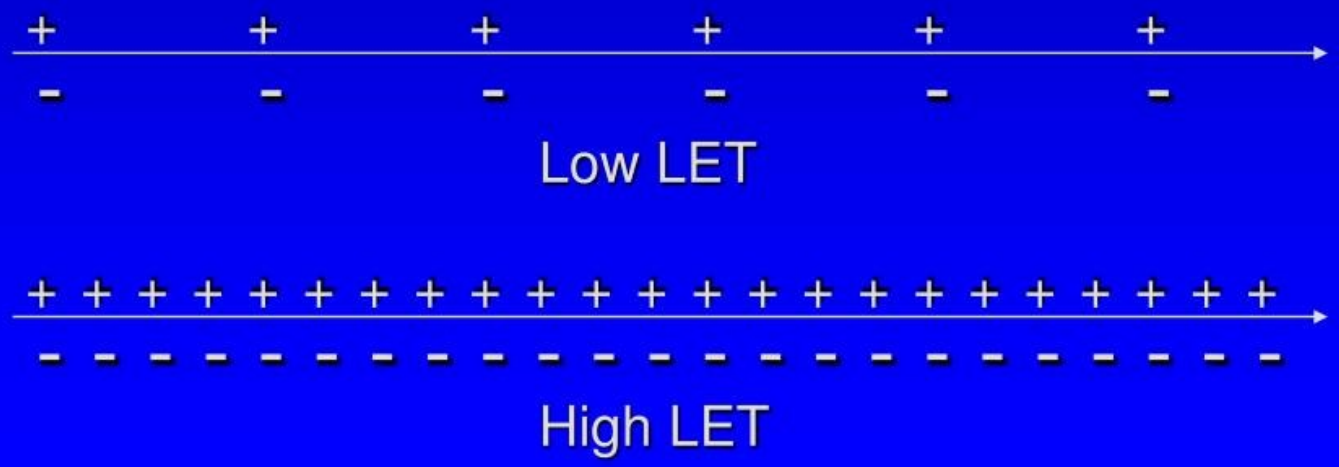
- Radiation type properties
  - Penetrating power
  - Linear energy transfer (LET)
- Exposure type
  - External vs internal
  - Acute (minutes or less)
  - Chronic (days or longer)
- Dose (amount of energy deposited in body organs)

Penetrating Properties of Ionizing Radiation



Linear Energy Transfer (LET)

- The amount of energy deposited per unit path length
- High LET Radiation is more damaging



Relative Relationship of Radiation Range to LET

Radiation	Relative Range	Relative LET*
Alpha	1	10,000
Beta	100	100
Gamma	10,000	1

* Linear Energy Transfer – energy deposition per unit of distance traveled

Alpha and Beta Ranges in Air

Radiation	Range in Air
Alpha (4-5 MeV)[a]	1-2 inches
Beta – 0.1 MeV	4 inches
1.0 MeV[b]	12 feet
3.0 MeV	43 feet

Notes:

a. Alpha energy associated with Uranium, Thorium, and Plutonium decay

b. Average maximum energy of beta particles from fission products is about 1.2 MeV

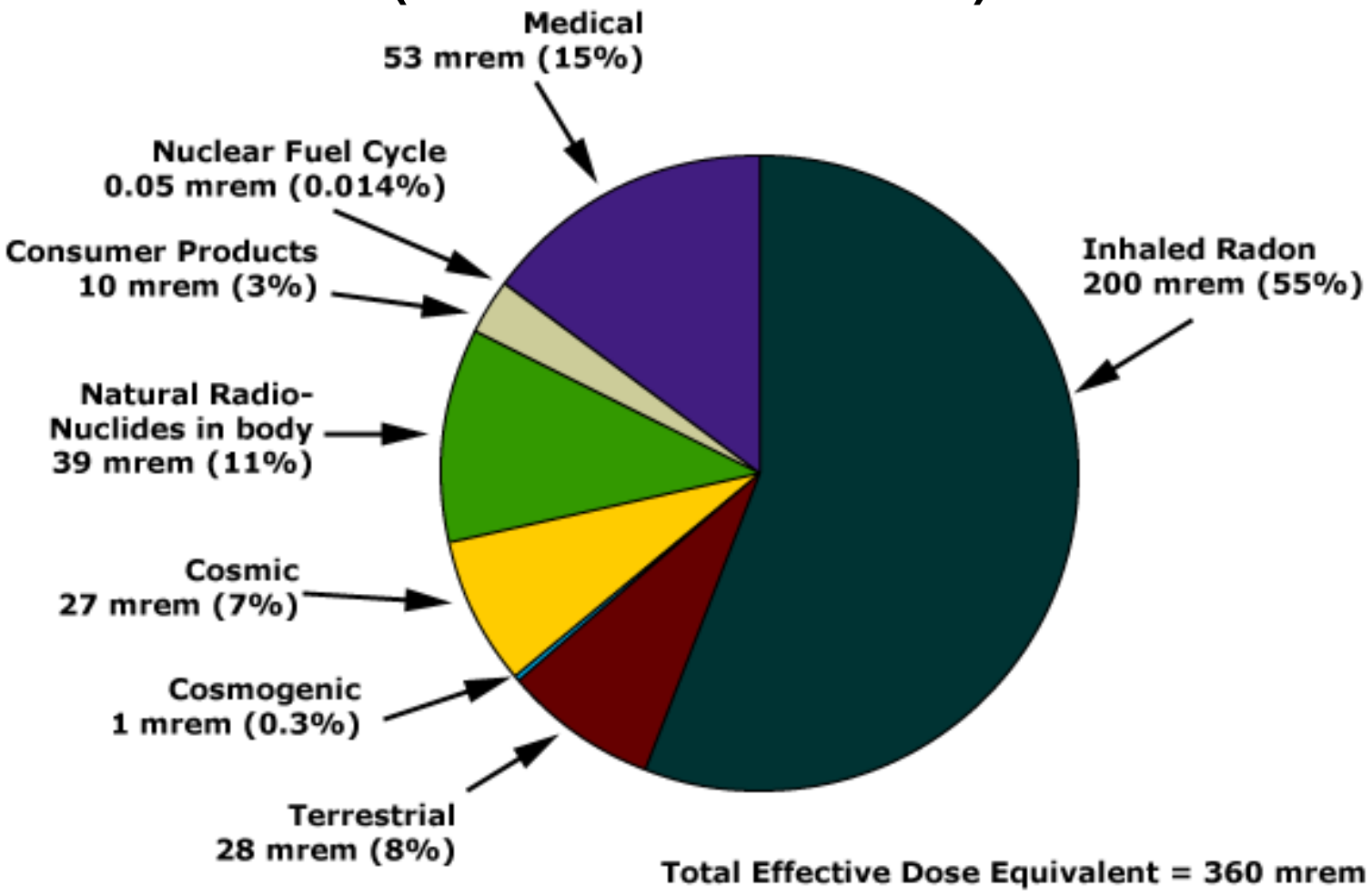
External vs Internal Radiation Exposure

- **External** radiation hazards – gamma-rays and x-rays
- **Internal** radiation hazards
  - Result from inhalation or ingestion of alpha- and beta-emitting sources
  - Concern about skin and clothing contamination with alpha and beta sources is proximity to pathways for inhalation and ingestion

Dose Types

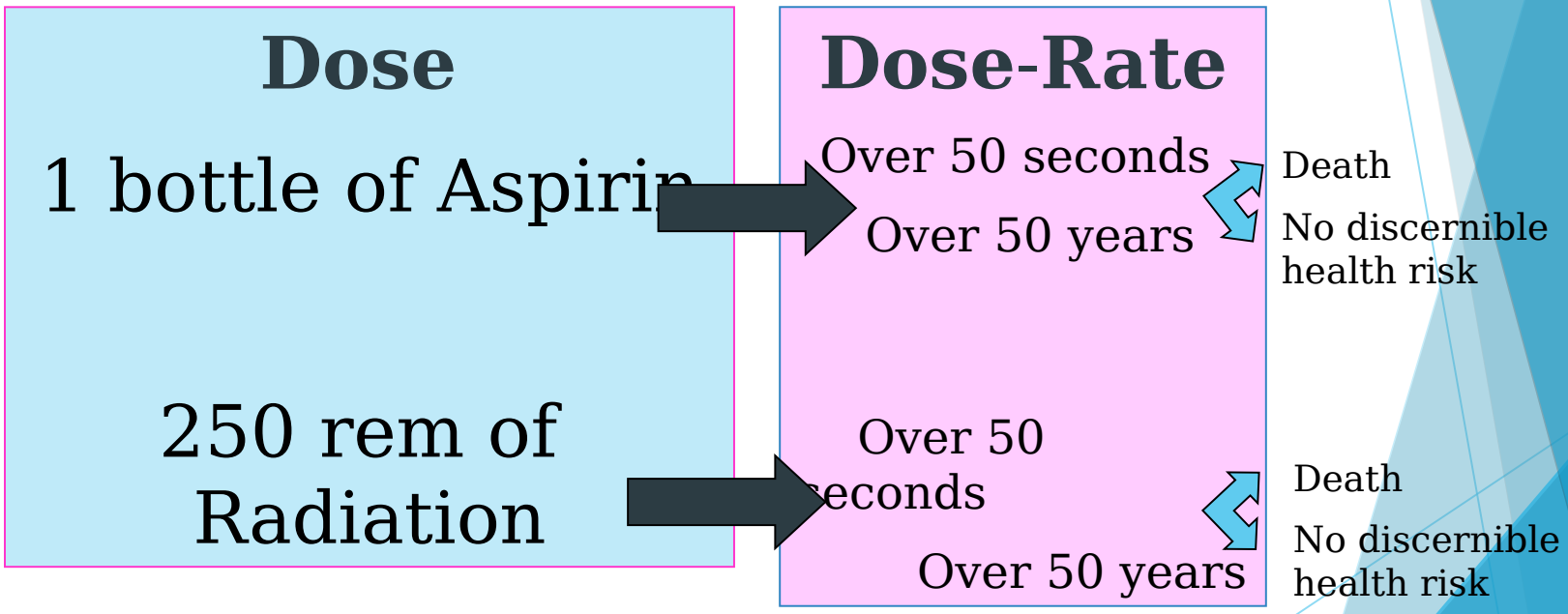
- Acute Dose
  - Dose delivered over a short period of time (e.g., chest x-ray)
- Chronic Dose
  - Dose delivered over an extended period of time (e.g., natural background radiation)
- Dose Rate Effect
  - Acute dose may be more damaging than chronic dose of same magnitude if cell damage overwhelms body's natural repair mechanisms

Sources of Natural Background Radiation (Chronic Doses)



Dose-rate Example

Health risk dependent on dose-rate



Quantifying Dose

- Absorbed dose (Gray)
  - Energy deposition per unit mass of material
- Equivalent dose (Sievert)
  - Absorbed dose to individual organs or tissue adjusted to account for biological effectiveness of radiation type
- Effective dose (Sievert)
  - Whole body dose calculated by adding equivalent doses to all organs, each adjusted to account for organ sensitivity to radiation type

Absorbed Dose

- Radiation Absorbed Dose (rad)
  - Originally defined as 100 ergs of energy absorbed by one gram of matter
  - 1 rad = 10^{-5} Joule absorbed by one gram of matter
- International Standard – Gray [Gy]
  - 1 Gy = 100 rad

Radiation Biological Effectiveness

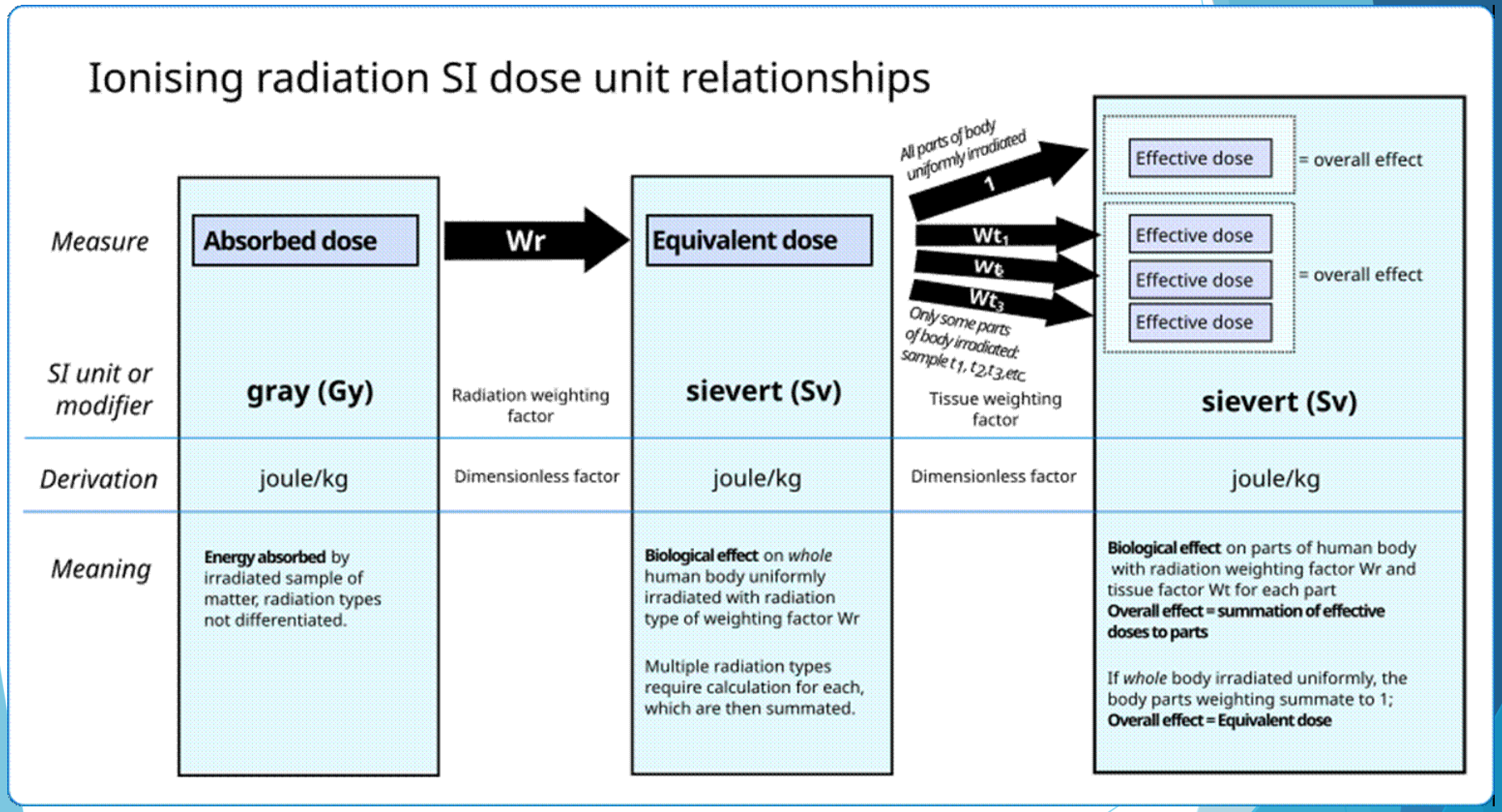
- Depends on absorbed dose and LET
- Effect on biological systems quantified using upper limit of radiation's relative biological effectiveness, called quality factor (QF)

Radiation	Quality Factor
X-rays	1
Gamma radiation	1
Beta particles	1
Alpha particles	20

Equivalent Dose

- Represents *POTENTIAL* for organ/tissue biological effects
- Provides common reference and allows for additive doses for different radiation type exposures
- Historical/conventional unit - rem
  - Dose (rem) = QF x Dose (rad)
- International Standard – Sievert [Sv]
  - Dose (Sv) = QF x Dose (Gy)

Absorbed Dose to Effective Dose


Ionising radiation SI dose unit relationships
Measure
SI unit or modifier
Derivation
Meaning
Absorbed dose
gray (Gy)
joule/kg
Energy absorbed by irradiated sample of matter, radiation types not differentiated.
Wr
Radiation weighting factor
Dimensionless factor
Equivalent dose
sievert (Sv)
joule/kg
Biological effect on whole human body uniformly irradiated with radiation type of weighting factor Wr
Multiple radiation types require calculation for each, which are then summated.
All parts of body uniformly irradiated
1
Wt1
Wt2
Wt3
Only some parts of body irradiated: sample t1, t2,t3,etc
Tissue weighting factor
Dimensionless factor
Effective dose
= overall effect
Effective dose
Effective dose
Effective dose
= overall effect
sievert (Sv)
joule/kg
Biological effect on parts of human body with radiation weighting factor Wr and tissue factor Wt for each part
Overall effect = summation of effective doses to parts
If whole body irradiated uniformly, the body parts weighting summate to 1;
Overall effect = Equivalent dose

Radiation weighting factor (W_r) is same as QF

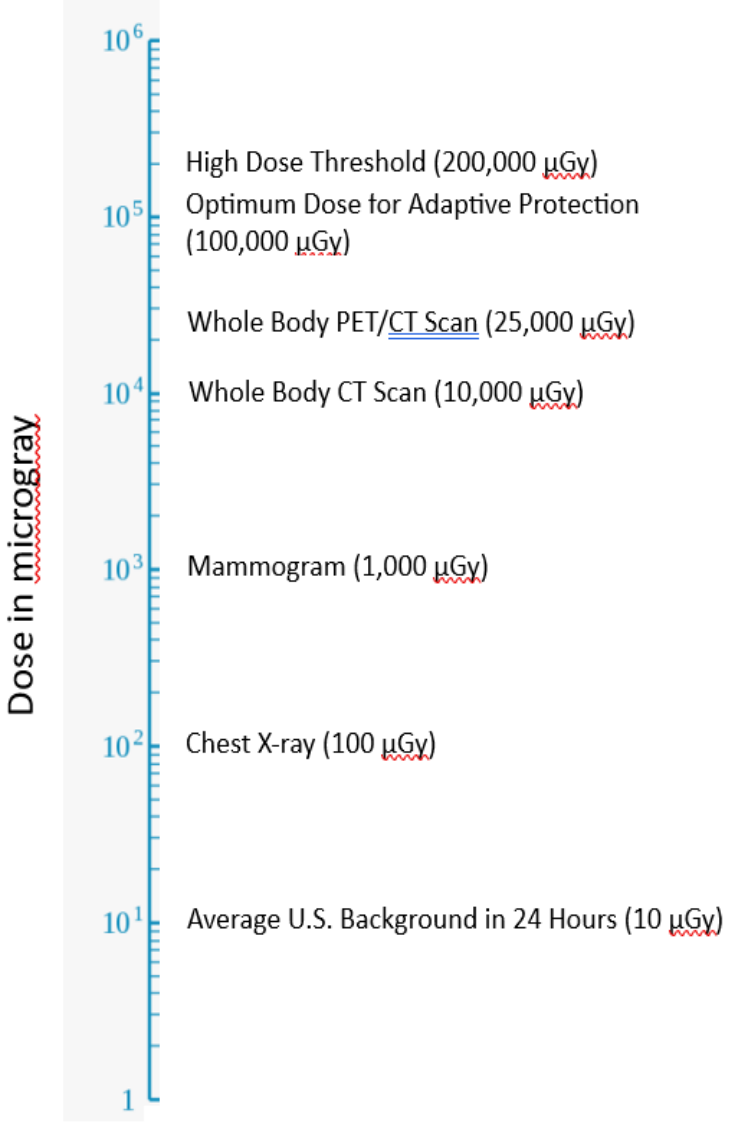
Tissue weighting factors (W_t) account for organ sensitivity to radiation type; sum of weighting factors for all organs and tissues in human body equals one

Summary of Radiation Terms and Units

	Traditional	**SI***
Activity	Curie (Ci) 3.7×10^{10} dis/sec	Becquerel (Bq) 1 dis/sec
Absorbed Dose	Rad	Gray (Gy)
Equivalent/Effective Dose	Rem	Sievert (Sv)

* Abbreviation for International System of Units

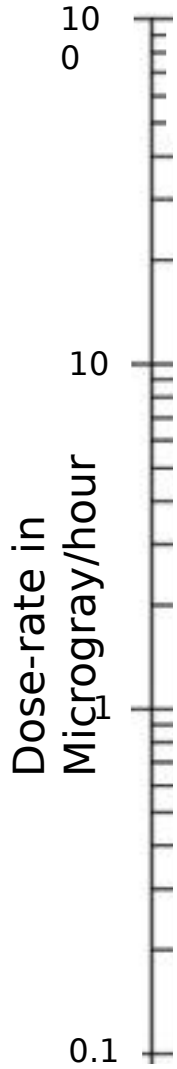
Acute Exposures in Perspective



Public acute (medical) exposures to low LET ionizing radiation orders of magnitude below threshold for biological harm

Low LET radiation contributes only about 4.5 µGy to natural background radiation exposure

Chronic Exposures in Perspective



Low-LET High-Dose-Rate Threshold (80 µGy/hr)

U.S. public chronic exposures to internal and external ionizing radiation are well below thresholds for potential lifespan shortening

High-LET (Internal) High-Dose-Rate Threshold (1 µGy/hr)

U.S. average natural background absorbed dose-rates:
Low-LET – 0.12 µGy/hr
High-LET – 0.01 µGy/hr

Correcting a Radiation Exposure Misconception

- Exposure to ionizing radiation does not make humans, animals, or food radioactive; only deposits energy in matter
- Only way to make an atom radioactive is to change ratio of neutrons to protons in atomic nucleus
- Ionizing radiation only interacts with atomic electrons and has no effect on number of neutrons and protons in atomic nucleus

Dose Reduction Measures

- Restrict exposure (proximity) *TIME*
  - Dose = Dose Rate x Time
- Maximize *DISTANCE* from radiation source
  - Point source: “1-over-R-squared” reduction in dose with distance (R)
- Use *SHIELDING* material to reduce radiation emitted from source